BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

B69 12076

SUBJECT: Some Space Shuttle Technology Considerations - Case 105-3

DATE: December 29, 1969

FROM: D. E. Cassidy

ABSTRACT

The Space Shuttle represents a substantial advancement in spacecraft and launch vehicle design. New systems will have to be developed and advances will have to be made to the state-of-the-art in many technology areas to meet the goal of low recurring cost. Better understanding will be required of aerodynamics and structural scaling effects as well as material properties. Also, the allowable level of degradation for systems reuse will have to be determined, and failure detection techniques developed.

This memorandum addresses some of the major technology issues associated with the Space Shuttle development with the intention of suggesting areas which require concentrated effort.

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MEMORANDUM FOR FILE

INTRODUCTION

The Space Shuttle, as currently conceived, is a reusable, two-stage round trip to earth orbit transportation system consisting of a booster and an orbiter. The two-stage system will deliver a total weight to earth orbit (270 nm, 55° inc.) somewhere around 250,000 pounds, consisting of a discretionary payload of 50,000 pounds and a reusable orbiter vehicle of about 200,000 pounds. The total impulse ΔV for the mission would be nearly 32,000 fps, including on-orbit and deorbit maneuvers. Some idea of the magnitude of this task can be obtained from noting that the three-stage Saturn V does not have the capability of imparting an impulse ΔV of 32,000 fps to a weight of 250,000 pounds. As a result of this relatively large impulse ΔV and large inert weight of the orbiter, the Space Shuttle performance will be very sensitive to inert weight growth of the structure and systems during development, and any engine performance degradation.

Since the orbiter inert weight will be around 4 to 5 times the payload weight, and in the orbiter stage the payload and inert weights are traded pound for pound, fractional increases in the orbiter structural weight will be amplified in payload reductions. This effect is particularly significant since over 90% of the orbiter dry (or inert) weight is due to some form of structure and over 30% of that is thermal protection. Only a 1 mil increase in outer skin thickness of the orbiter (considering a metallic heatshield), as an example, would equal about 700 pounds of payload. (Writing paper is 2 to 3 mils thick.)

The effect of this sensitivity is further illustrated in parametric form on Figure 1. The chart on Figure 1 presents the percent change in the Space Shuttle nominal payload (payload sensitivity) due to a percent change in the stage inert weight and a percent change in the specific impulse (Isp) of the engines. The sensitivity to Isp is plotted on the ordinate and the sensitivity to inert weight is plotted on the abscissa. The data bands in Figure 1 reflect differences in design assumptions and staging velocity for the two stage Space Shuttle data presented in References 1 and 2. For the purposes of comparison, payload sensitivity for the stages of the Saturn V (SIVB, SII, SIC) is also included. The payload of the Saturn V, in this case, is taken to be the Translunar injection payload of a typical lunar mission.

In figure 1 it is assumed that one stage or the other experiences the degradation. If both stages do, the combined effect would be larger. The main point of these charts is to emphasize that the Space Shuttle vehicle represents a sensitive system with tight margins, and that the development of many new subsystems to meet high performance and reusability requirements of the Space Shuttle will require weight and performance controls far more stringent than were necessary to develop the Saturn V launch vehicle.

Although the impact of technological risk on development program cost, schedule and operational effectiveness is difficult to assess at this time, some general remarks can be made concerning the major development activities necessary to the Space Shuttle development.

TECHNOLOGY AREAS

The NASA Space Shuttle Technology Group has identified the following six major technology areas as essential to achieving the objectives of the Space Shuttle program.

1. Aerodynamics and Thermodynamics
2. Dynamics and Aeroelasticity
3. Structures and Materials
4. Propulsion
5. Integrated Electronics
6. Human Factors and Life Support

Some of the Space Shuttle objectives are tabulated in Figure 2 with the technology areas having major influence indicated with darkened squares. The qualitative influence of the technology areas on Space Shuttle objectives illustrated in Figure 2 will be expanded somewhat in the following discussion in order to point out some of the issues involved in achieving the Space Shuttle technology goals.

An estimated technology program schedule is presented in Figure 3. This schedule was taken from Reference 3 and gives some idea of the close timing which is presently projected for the Space Shuttle program. Because very little direct technology work has been started since this schedule was prepared last June, it should be extended about six months. Also, recent activities of the Space Shuttle Technology Group indicate that the Structures and Materials activities schedule of Reference 3 is too optimistic and should be extended at least through CY 1972.

Although the Space Shuttle development is considered feasible, the timing is close and technological risk is high. It requires that a considerable amount of work be completed between now and configuration freeze. Data generated on small models and apparatus must be scaled by as much as one or two orders of magnitude for full scale use or large scale models and apparatus will have to be built. It must be decided, then, how close the R&D models should be to the finished article, or should the models in fact be prototypes.

AERODYNAMICS AND THERMODYNAMICS

The aerodynamic configuration evaluation and definition (both air loads and thermal loads) will have an impact on the other technology areas, and in particular, on the Dynamics and Aeroelasticity and the Structures and Materials. The aerodynamics and thermodynamics will have to be evaluated through the entire Mach number range from 0 to 25 including the two-body launch configuration and separation conditions. Much of the present test data generated in wind tunnels on models approximately one to two feet long, and to a limited degree verified by flight tests, are not directly applicable to the Space Shuttle. Orbital and near orbital velocity flight test data were obtained on the 8 and 6 foot long Prime and Asset vehicles; low hypersonic, transonic and subsonic data were obtained on the 55 foot long X-15; and subsonic and transonic data were (and are being) obtained on the 22 to 24 foot M2-F2, HL-10, and X-24 lifting body vehicles. The different configurations proposed for the Space Shuttle as well as the larger vehicle size (booster over 200 feet, orbiter over 150 feet) compared to these other aerospace vehicles will necessitate extensive testing to establish design criteria. As an example, although Newtonian theory works quite well hypersonically at the lower altitudes, the viscous effects at low Reynolds number during initial entry will reduce L/D. This reduction in L/D would be lower for the larger vehicle than a smaller model. In addition, the effects of the boundary layer state and flow separation would effect the aerodynamic heating as well as change the vehicle trim and control effectiveness, depending on vehicle size.

During the ascent phase of the mission, the oblique shocks generated by the various elements of the two vehicles will interact and impinge upon surfaces, generating localized hot spots and requiring increased thermal protection weight. This effect is particularly important at the high dynamic pressures expected during the planned ascent trajectory which has a 45 nm injection altitude. The dynamic pressures ranging from 20 to 50 psf at parallel stage separation will also require extensive data collection for stability and control. Some early testing at the Langley Research Center (Reference 4) indicated adverse conditions when parallel staged vehicles are separated. The orbiter lift curve slope tends toward zero, and an induced negative pitching moment on the orbiter could require a separation propulsion system or a large separation mechanism. Active RCS might be required to limit displacement excursions during stage separation as well as during reentry where marginal stability and low aerodynamic damping require stability augmentation. RCS sizing can be quite sensitive to these varying requirements and might have to be considerably oversized pending firm design requirements.

The subsonic characteristics of both the orbiter and booster will have to be a compromise between desired landing requirements and payload penalty, with consideration to system complexity. High values of L/D and C_L are important for the low speed operations since high L/D reduces the glide slope as well as propellant weight and engine size for cruise and landing abort go-around, while high C_L reduces the approach and landing velocity. Since high values of L/D and C_L require body shaping, lifting surfaces (e.g. wings) and augmentation devices (e.g. flaps), the payload to orbit is reduced if high L/D and C_L are required for cruise, slow speed landing and go-around. However, without these subsonic characteristics airplace type flight testing would be curtailed.

Subsonic flight is also effected by surface roughness. Recent wind tunnel tests at the Ames Research Center (Reference 5) indicate significant reduction in L/D and Cm_{α} as well as a change in trim for an X-24 lifting body with a simulated honeycomb reinforced charred ablative surface. These effects would have to be considered if an ablator is used as an interim or alternative to a radiative heat protection system.

DYNAMICS AND AEROELASTICITY

The same general comments can be made for this technology area as for Aerodynamics, since the aerodynamics are the significant forcing functions of the vehicle dynamic response. However, the vehicle mass, mass distribution, and structural stiffness introduce additional dimensions to the problem. Not only are aerodynamic parameter simulations required, but mass and material scaling is necessary as well. The design will be dependent upon test and evaluation of different vehicle configurations, materials, and structural techniques.

Noise and vibration data from the boost engines can be predicted to some extent based on previous experience gained on large launch systems, but air noise and unsteady air flow during ascent and descent will require detailed testing. Aeroelastic effects causing flutter and configuration distortions will depend on structural stiffness and methods of joining skin panels. The effect will be particularly significant for cantilevered elements such as stabilizing surfaces, control surfaces, and lifting surfaces. Scaling wind tunnel and other test data one or two orders of magnitude can introduce considerable risk. It is not known, however, how much more risk is involved in scaling two orders of magnitude as compared to one.

STRUCTURES AND MATERIALS

Since the payload delivering capability of the Space Shuttle will be very sensitive to inert weight, this area of technology will be particularly significant. The conventional methods of aircraft construction using aluminum alloys, steel and titanium alloys might not provide sufficient payload margin. New, and somewhat exotic, composite materials and structural techniques may be required to reduce structural weight to a minimum. Limited applications of boron composite material for aircraft structures have indicated potential weight savings of from 25 to 50% (Reference 6), but with increased complexity and cost of fabrication. Extensive use of this or other composites on the Space Shuttle could require the development of new manufacturing processes and airframe assembly procedures. An alternative approach being studied by AVCO (Reference 7) in which aluminum channels, T's and I's are reinforced by inserting composite elements within the aluminum may allow the use of conventional assembly techniques. Further evaluation of the application of composite materials to the Space Shuttle is necessary.

The interface of the main load carrying structure and the thermal protection system also requires extensive analysis. The selection of materials for the Space Shuttle will depend on whether the load structure can be hot and how hot. The hot structure approach of utilizing the load structure as a heat shield and insulating the inside face of the load structure has been demonstrated on the 6 foot ASSET vehicle and a 6 foot section of a conceptual aerospace plane design (ASCEP) using columbium, tantalum and superalloys (Reference 8). These demonstrations indicate that the integral hot structure is feasible and can save structural weight, although forming various shapes to withstand thermal stress, as well as the structural analyses, can be very difficult. In addition, the hot structure approach does not lend itself to the use of ablative panels for interim and alternative use. Silica elastomeric spray similar to what was used on the X-15, however might be applicable.

The alternative approach of a cool load structure and stand-off heat shield simplifies many of the problems but potentially has the highest weight. The load structure can be optimized at low temperatures to obtain high material strength and minimum thermal stress. The heat shield can be optimized for heat rejection at the expected temperature range. Furthermore, this approach permits fabrication of flat panels and relatively simple shapes.

The high temperature materials available for the heatshield tend to fall into temperature ranges as follows:

ZrB_2

3000°F —

Tantalum

2400°F —

Columbium, LI-1500

2200°F —

TDNiCr

1800°F —

Superalloys

1000°F —

There are a relatively large number of superalloys available for heatshield use below 1800°F, but the material selection is very limited above 1800°F. A major consideration for selecting heat shield materials is the requirement for multiple reuse. Although all these materials have been tested for physical properties in the temperature ranges indicated, how multiple reuse of the materials can be tested and guaranteed for the Space Shuttle has yet to be determined. One of the major concerns is that the scaling of data obtained on small test coupons has been unreliable in some cases in the past.

Columbium and tantalum require oxidation resistant coatings which also must be reusable, since coating replacement or refurbishment would be more complex than changing the ablator panels. For the same gage panel, tantalum is twice the weight of columbium so that columbium would be desirable up to 2400°F. However, depending on the alloy of columbium, unacceptably large high temperature creep might occur which would warp the surface as well as degrade the coating. Unfortunately, an optimum columbium alloy has not yet been found for Space Shuttle work and there might not be sufficient time for its development, so that an existing alloy with limited reuse capability would have to be used. An alternate to columbium is a compacted silica fiber material (LI-1500 and HCF as examples) which acts as an external insulator and to some extent (as yet undetermined) an overheat ablator. Whereas columbium has creep tendencies, this material has shrink tendencies depending on how it is cured (Reference 9).

Various diboride composites (ZrB_2 +---) have been developed by Man Labs, Inc. (Reference 10) for multiple reuse at temperatures as high as 5000°F. These materials, however, are brittle at low temperatures and could require handling similar to glass. The diboride materials are presently only being fabricated and tested in 3 inch radius sizes, which again would involve the question of scaling.

TD-Ni-Cr is being fabricated by Fansteel, Inc. in 20 mil gage panels as large as 2 feet by 4 feet, (Reference 11). This material holds promise up to 2200°F since it resists oxidation without the need for coatings. TD-Ni-Cr presently has the opposite problem of columbium, namely embrittlement at 2200°F. Physical property improvement, 10 to 12 mil gage, and large scale production are required for the Space Shuttle applications.

The high temperature insulation material selection seems to be limited to Micro-Quartz up to 1650°F, Dyna-Flex up to about 2800°F and Zi-conia felt above 2800°F, (Reference 12). The combination of high temperature and high noise levels from the air flow causes degradation of most high efficiency, low density insulation materials. Micro-Quartz can be made in densities of 3-6 pcf, Dyna-Flex in densities of 8-10 pcf and Zirconia felt in densities of 14-63 pcf. Again, the price of the more severe environment is reduced payload if high efficiency low weight insulation cannot be developed.

PROPULSION

The main propulsion system will require the development of a large (400,000 pounds thrust or greater) restartable and multi-reusable LOX-hydrogen engine. In order to achieve higher performance than any previous LOX-hydrogen system, the engine, as conceptually planned, will operate at a chamber pressure of approximately 3000 psi and have an extendable, two position bell nozzle for altitude compensation. Whether a single engine size will be satisfactory for both the booster and the orbiter, or two different sizes are required will entail further analysis. Too large an engine in the orbiter detracts directly from the payload while too small an engine in the booster requires a large number of engines and therefore complicates the plumbing and increases the base area.

The sensitivity of the engine performance to mixture ratio will have to be well understood before the booster and orbiter vehicle sizes are fixed. The reduced specific impulse of the engine at high mixture ratios must be balanced against the larger hydrogen tankage required at the lower mixture ratios before the vehicle design can be frozen.

INTEGRATED AVIONICS

The avionics system technology efforts can be separated into five closely coupled areas of investigation:

1. Vehicle Control and Operations (G&N, Flight Control, Communications)

2. Systems Checkout and Diagnostics

3. Information Management and Display

4. Power and Power Distribution

5. Systems Reliability and Maintenance (MTBF and repair)

The avionics systems will perform a multitude of functions and be actively involved in every operation on the Space Shuttle. It will be essential to the autonomous operation of the shuttle and require a minimum of crew displays. Although the avionics will typically represent less than 4% of the orbiter stage inert weight, its weight is of the order of one-fifth to one-fourth that of the payload itself and therefore will certainly be an important consideration.

The development cost of the avionics system for recent high performance aircraft has averaged nearly 50% of the total development cost. With a price tag of over 5 billion dollars for the Space Shuttle development program, the avionics systems cost will be high. In addition, the extent to which the avionics system can be used for onboard checkout and malfunction diagnostics, the component mean time between failures, and the component accessibility for maintenance, will have a major effect on the Space Shuttle operations cost.

The Space Shuttle integrated avionics system as currently conceived will rely heavily on computer control and data storage. The extent to which the various avionics systems can be integrated will depend on the development of a central multiprocessor and high traffic rate data bus network. The data bus network would tie the entire avionics system together for computational services, malfunction detection and diagnostics. Substantial design analysis will be required to resolve such issues as the tradeoff between component redundancy and the development of new high reliability, long life systems. In addition, component malfunction criteria and corrective action strategies will have to be established for all the subsystems.

HUMAN FACTORS AND LIFE SUPPORT

The primary impact of men in the Space Shuttle will be the requirement for the preservation of a high probability of survival through each mission from the maiden flight to the final flight of each shuttle vehicle. Degradation of systems and components effecting survival must be detectable so that corrective action can be taken, and sufficient redundancy must be provided to back-up failures which exceed acceptable occurrence probabilities. If high reliability cannot be continually maintained to the levels of either military attack aircraft or commercial airlines (in one case crew back-up escape systems are provided, in the other they are not), abort capability will be required. Intact abort or crew escape from any point in the mission could impose excessive penalties. For example, with present designs, during the first ten seconds or so after launch, there is not sufficient time to start the orbiter engines to separate from the booster. The addition of an escape capsule and escape rockets would cost at least 15,000 pounds of payload* to say nothing of the impact of such a system on the shuttle design.

Some of the other aspects of human factors that will have to be investigated are:

1. The life support systems including waste management and CO_2 removal (these might be scaled up versions of the Apollo System);

2. The crew size for command and control as well as operations support, and the crew compartment size considering either the inclusion of passengers or a separate module;

3. Physical strain on passengers due to the ascent accelerations, vibrations, ingress and egress procedures;

4. The extent to which the crew will control the vehicle from lift-off to landing and the impact on the vehicle response and landing characteristics.

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D. E. Cassidy

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*Estimation based on the 12 man Big G, Reference 13.

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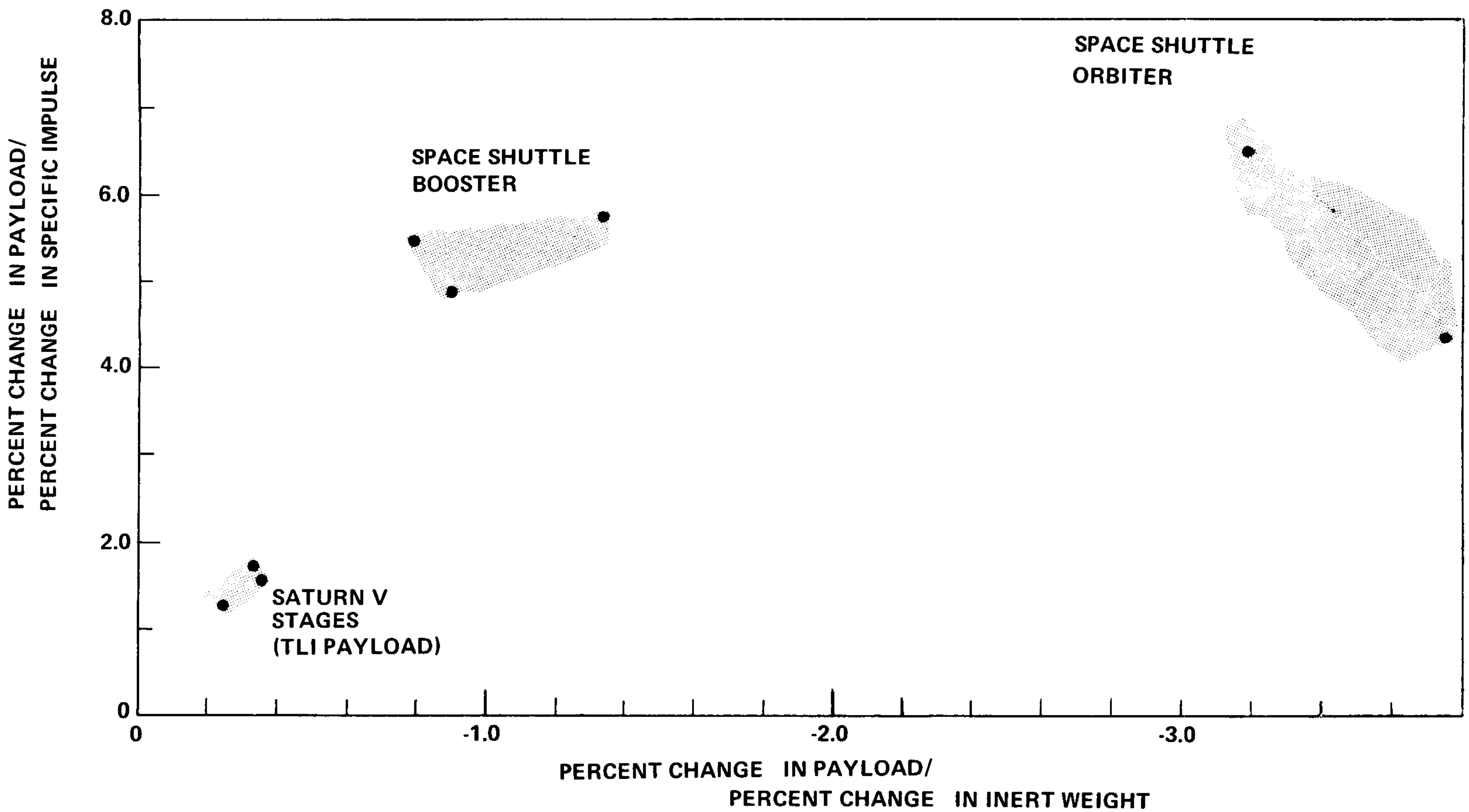

FIGURE 1 - SPACE SHUTTLE PAYLOAD SENSITIVITY TO CHANGES IN STAGE INERT WEIGHT AND ENGINE SPECIFIC IMPULSE. (BASED ON 50,000 LBS. PAYLOAD 15' X 60')

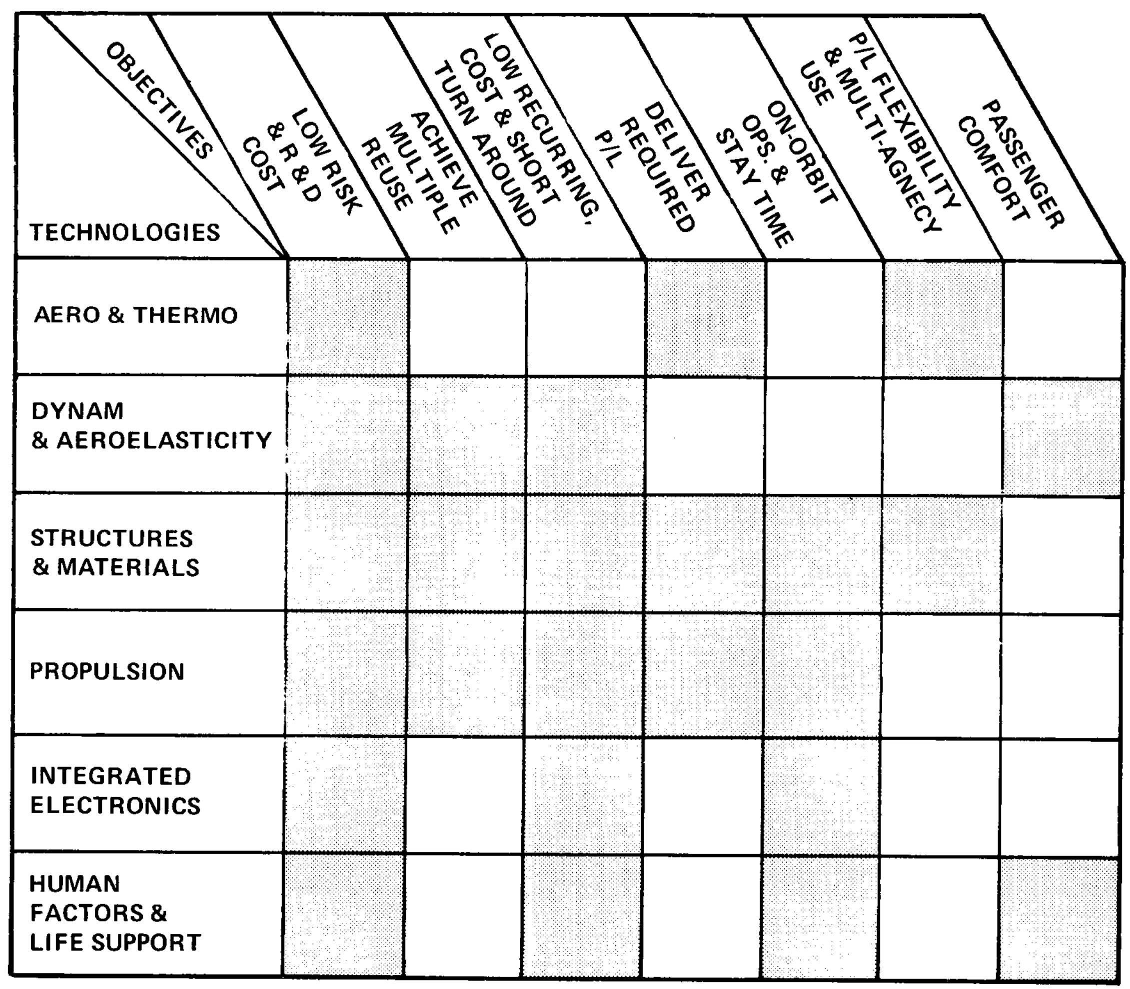

FIGURE 2 · TECHNOLOGY AREAS AND MISSION OBJECTIVES

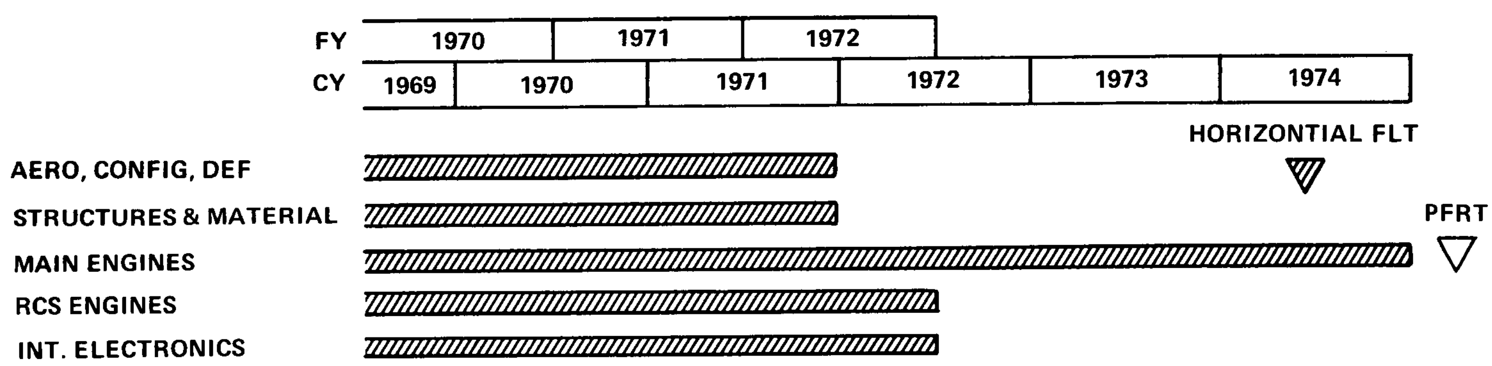

FIGURE 3 - TECHNOLOGY SCHEDULE

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Subject: Some Space Shuttle Technology Considerations - Case 105-3

From: D. E. Cassidy

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